Integrated Thermodynamic Modeling for a Launch Vehicle's Cryogenic Upper Stage Propellant Tank

Laurie K. Walls
NASA Kennedy Space Center

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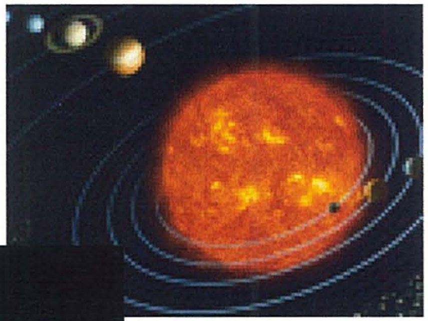
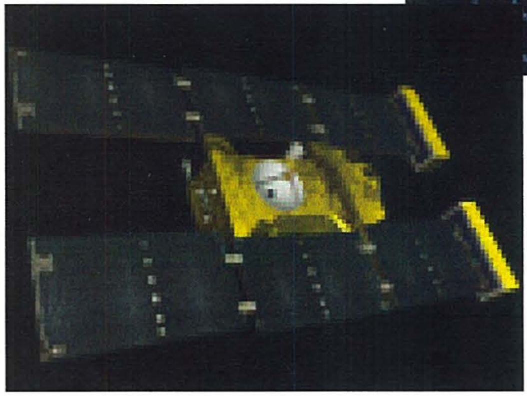
Introduction and Background

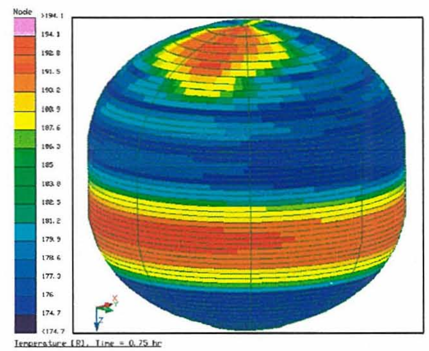
- Earth orbit and planetary (earth escape) missions necessitate precise control of propellants for long duration space environments
  - Cryogenic propellants necessitate use of accurate fluid management systems
    - Tank wall heat loads induce propellant warming and stratification
    - Vehicle maneuvers induce sloshing, increasing propellant warming and boil-off
    - Drives pressurization requirements and affects commodity mass
  - Current state of the art thermodynamic and thermal modeling typically performed independently
  - Models generally don't include fidelity to the level of
    - Boundary layer growth and energy/mass exchange
    - Stratification
    - Propellant slosh
    - Slosh baffles
    - Diffusion/evaporation
    - Gaseous helium infusion
    - Moving liquid vapor interface
    - Interactive thermal/thermodynamic coupling

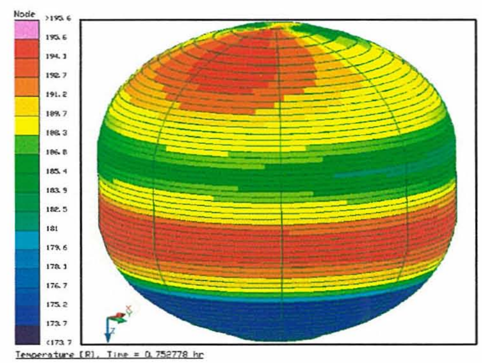




Model Description

- Fully integrated models developed to produce high fidelity predictions for propellant thermodynamic states and characterization
  - Utilizes industry standard tools
    - Thermal/thermodynamic: Thermal Desktop and SINDA/FLUINT
    - CFD: FLUENT, FLOW3D
  - Can accommodate complex geometries, ullage pressurization systems, propellant conditioning, boil-off, boundary layer growth, slosh effects
  - Accounts for
    - Proper liquid/wall interface area
    - Proper liquid/vapor interface area
    - Development of "warm" layer or stratum
    - Proper mixing of fluid and ullage
  - Includes
    - Fluid conduction: stratification, boundary layer development
    - Convection: boundary layer development, propellant boiling
    - Mass transfer: diffusion, vaporization, condensation
    - Pressurization and venting
    - Dynamic liquid /vapor interface areas and liquid/wall interface areas





- Flight and test data utilized to validate model predictions

Diffusion Modeling

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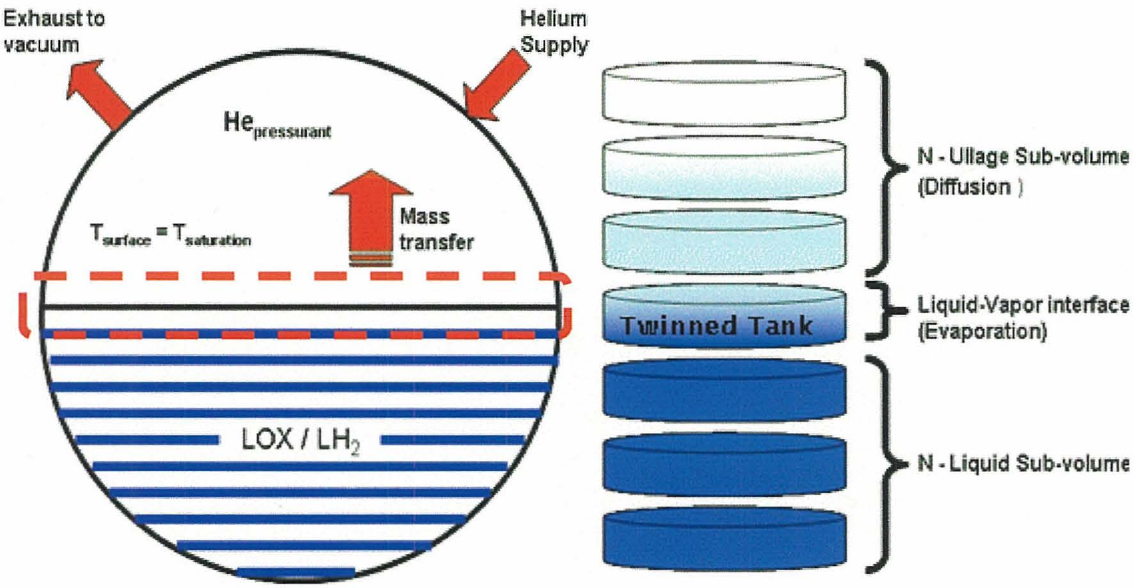
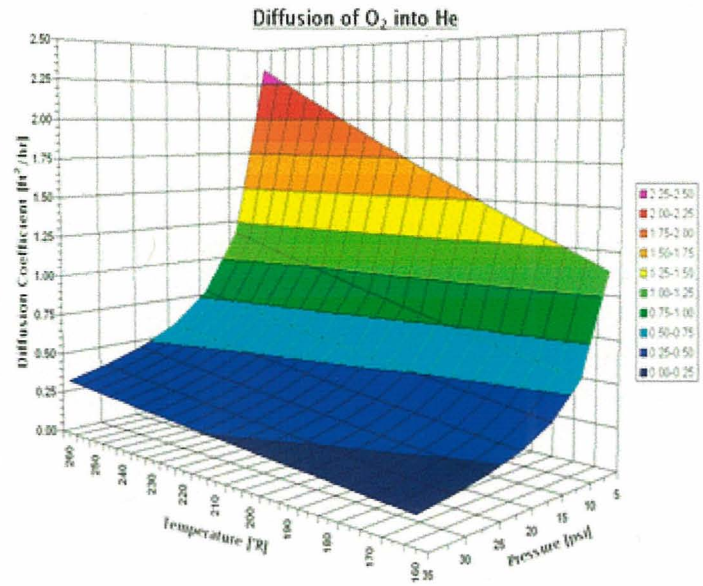
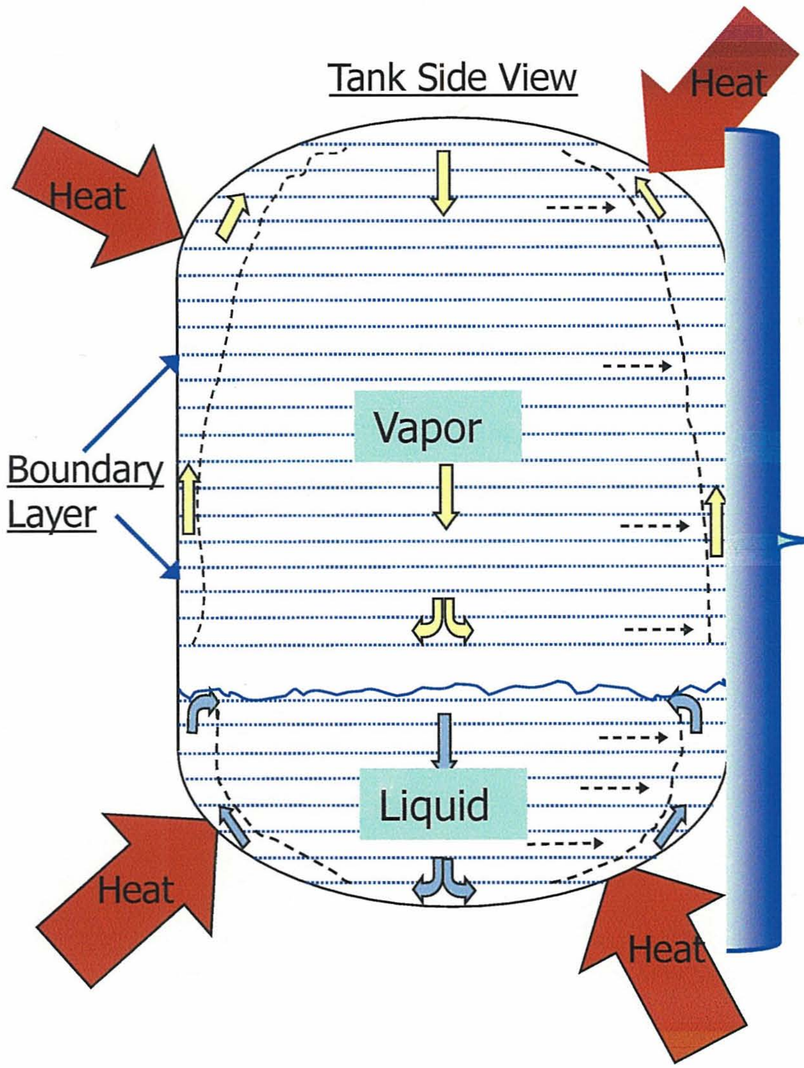
$$D_{AB} = \frac{0.02195 \; T^{3/2} \left(\frac{1}{M_A} + \frac{1}{M_B} \right)^{1/2}}{P \left(r_{AB} \right)^2 \left[f(\theta) \right]}$$





- Initial conditions for T, P and gas mass fractions are set via calls to FLUINT subroutine (Changes thermodynamic states of the lumps)
- Mass flow rate connectors are used to manipulate amount of mixing adjacent control volumes

Stratification Modeling



- **Stratification: "Temperature gradient within a fluid due to heat transfer by conduction and mass transport"**

- **For a container such as a tank, conditions at the wall are important**
  - **A temperature difference between wall and fluid**
  - **Heat transferred via conduction and fluid movement, 'boundary layer' (B.L.)**
  - **Fluid Behavior & fluid Properties**
  - **Wall Material**

Modeling Requirements

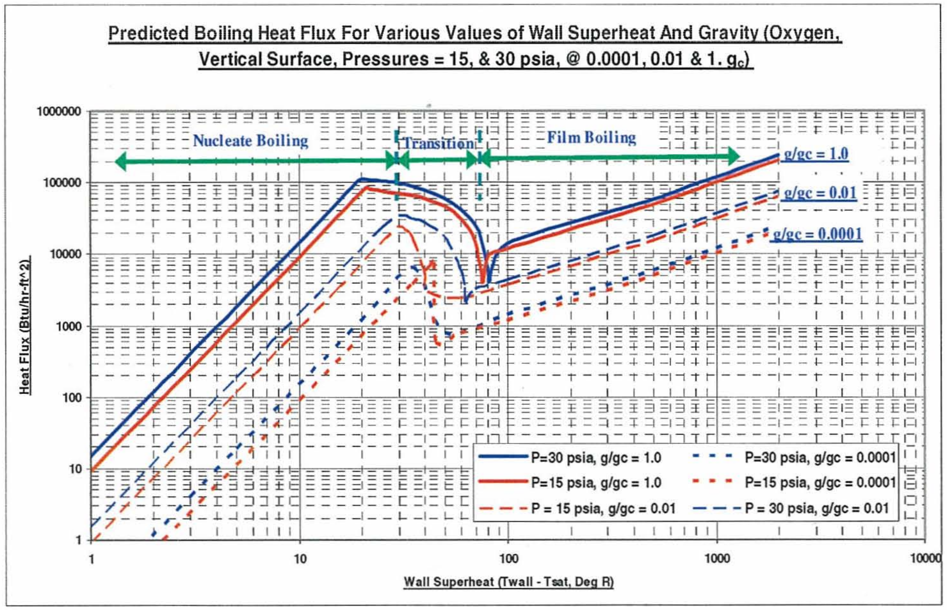
Sufficient resolution needed to capture stratification (number of strata)

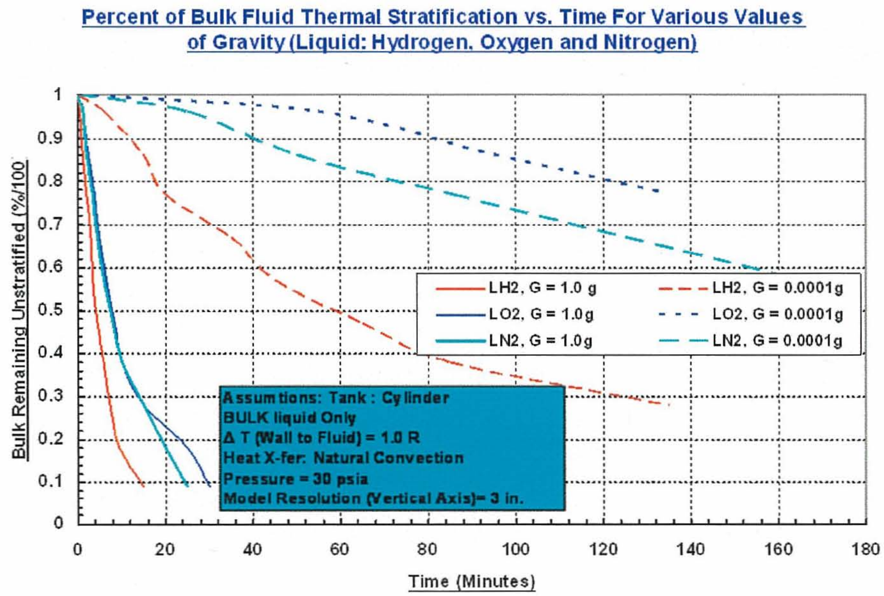
Varying gravity/acceleration → Local P & 'h'

Subroutines

- Local boundary layer thickness
- Mass flow rates
- Heat Transfer Coefficients

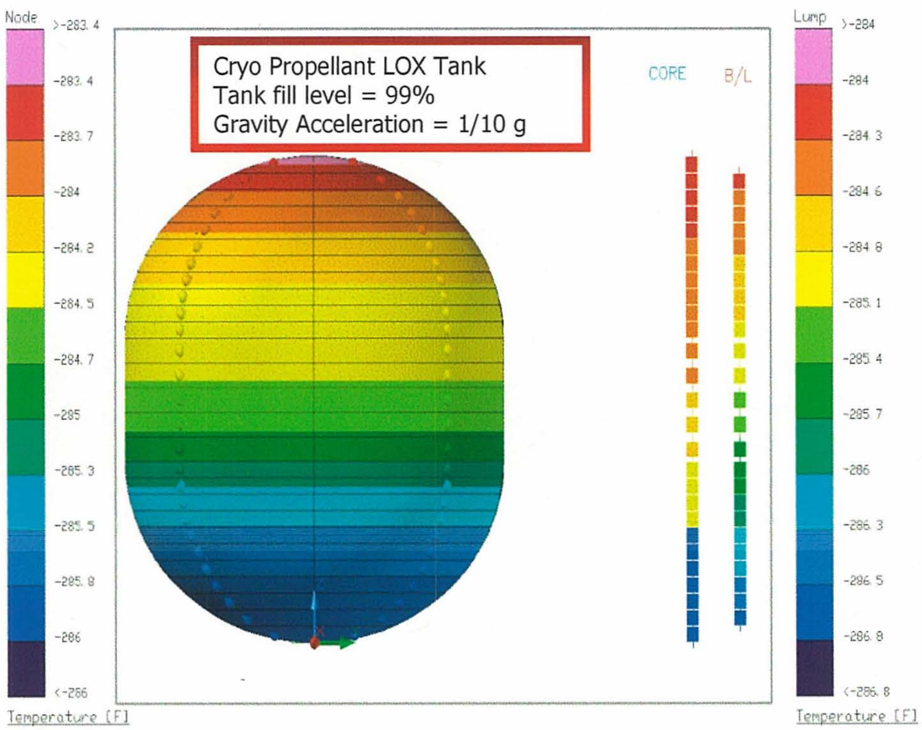
Stratification Modeling: Simulation Results

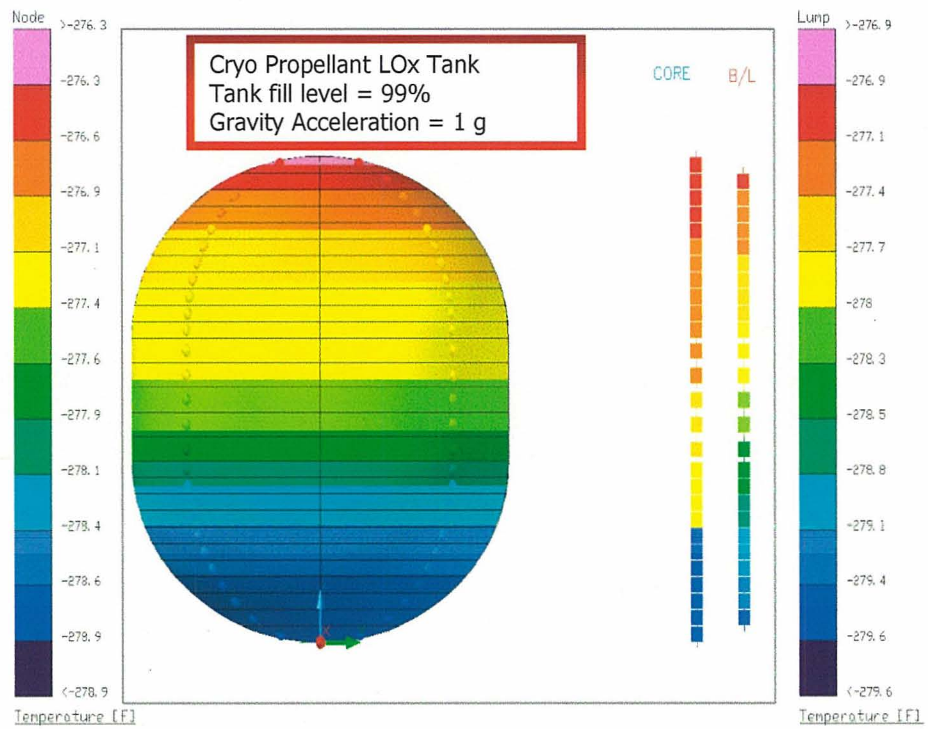




- Full range of Convective heat transfer regimes accounted for
- Boiling → phase change and convective and radiation heat transfer
- Boiling curves are unique for specific fluids
- Boiling regimes → phase change and convective and radiation heat transfer
  - Heat flux → [T_{wall} – $T_{Sat\ fluid}$] and various wall surface effects & fluid properties

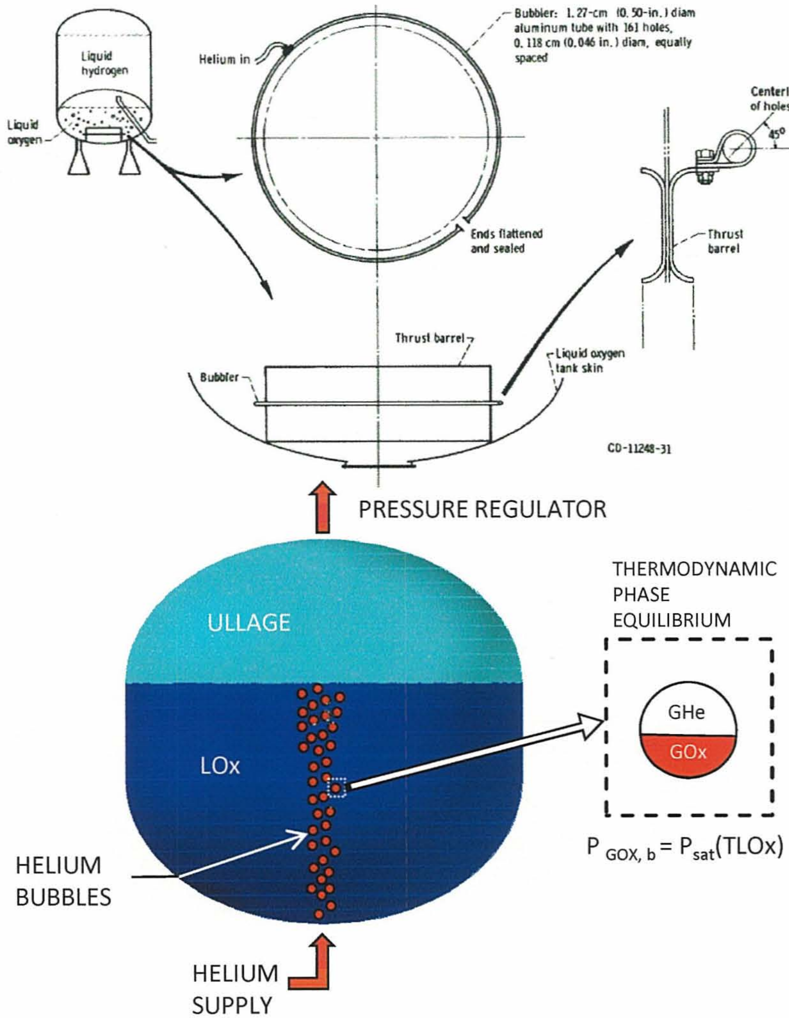
Stratification Modeling: Simulation Results





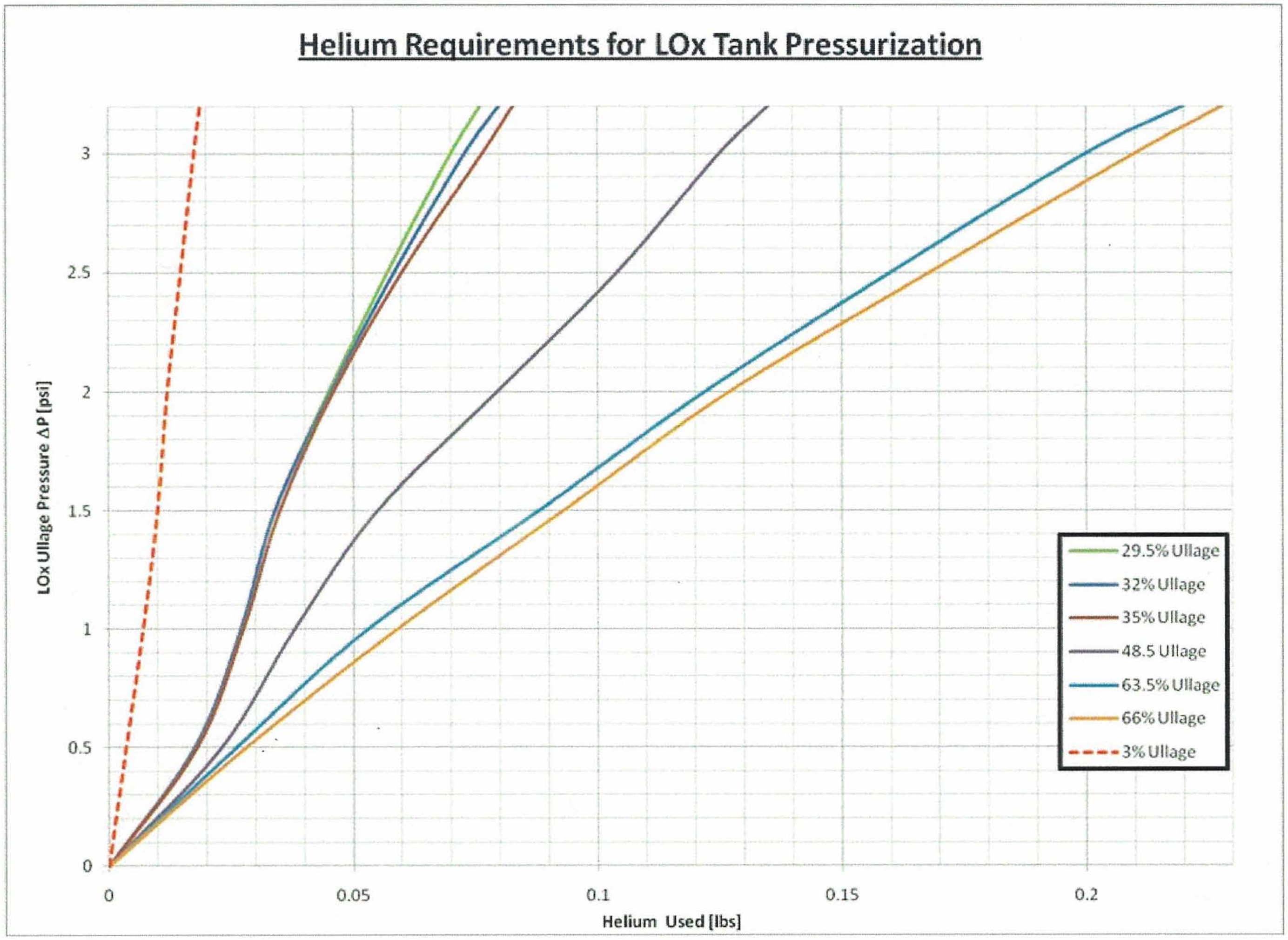
- Higher g = more buoyancy forces, higher stratification (relative), eventually more mixing
- Lower g = surface tension forces start having more of an effect, less of a buoyancy effect

Helium Infusion Thermodynamic Modeling



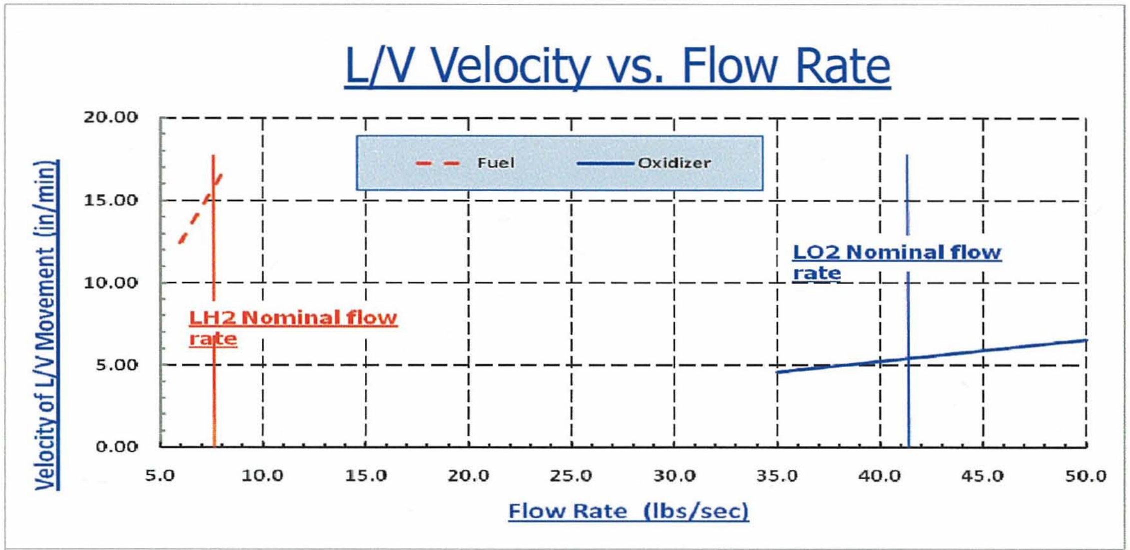
- Sub cooling of a cryogenic propellant by helium injection is one of the most effective methods for suppressing bulk boiling
- Implement finite rate heat transfer and instantaneous mass transfer model
- Oxygen continues to diffuse into the helium bubbles until thermodynamic phase equilibrium is reached i.e. when the partial pressure of oxygen vapor in the bubble is equal to the saturated vapor pressure of liquid oxygen at the particular temperature of the liquid
- The diffusion process (evaporation) results in a cooling effect caused by the vaporization heat of the surrounding liquid

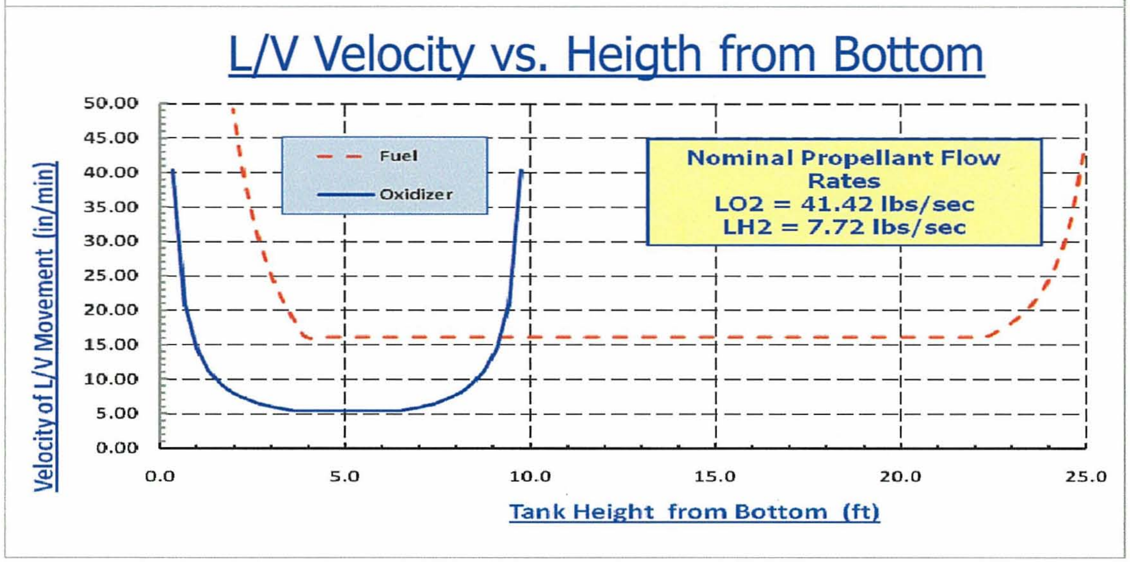
Example Helium Infusion Results



- Helium infusion is most effective with a small ullage percentage

Moving Liquid/Vapor Interface Modeling





Nominal Values Typical Cylindrical Section

LH2 ≈ 2.7 strata/min

LO2 ≈ 1 strata/min

CFD to Thermal Mapping

Wetted Fraction			
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0.000333	0	0	0.000333
0	0	0.000333	0
0	0	0	0
0	0.005	0.001	0
0.000333	0.347667	0.007667	0.003
0.003667	0.577667	0.017	0.007
0.005667	0.798333	0.038	0.011
0.009667	0.946333	0.167667	0.024667
0.124667	0.999667	0.547333	0.048333
0.404	1	0.993667	0.66
0.997	0.999	0.999333	0.997667
0.997	0.998	0.998333	0.996667
0.996	0.998	0.997333	0.996
0.996	0.997333	0.997	0.996
0.995667	0.997	0.997	0.995333
0.995	0.997	0.997	0.995
0.995	0.997	0.996	0.994
0.994333	0.997	0.996	0.994
0.994	0.997	0.996	0.993
0.993667	0.996	0.996	0.993
0.993	0.996	0.995	0.992333
0.993	0.996	0.995	0.992
0.992667	0.995333	0.994667	0.992
0.992	0.995	0.994	0.991333
0.992	0.995	0.994	0.991
0.992	0.994	0.993	0.991
0.991333	0.994	0.993	0.991
0.991	0.993667	0.993	0.991
0.991	0.993	0.992	0.990333
0.991	0.993	0.992	0.99
0.991	0.992333	0.992	0.99
0.991	0.992	0.992	0.99
0.991	0.992	0.991	0.99
0.991	0.992	0.991	0.99
0.991	0.992	0.992	0.99
0.991	0.992	0.992	0.99
0.991	0.992	0.992	0.99
0.9915	0.992	0.992	0.99
0.992	0.992	0.99125	0.99025
0.995667	0.995333	0.995667	0.994833

Wet?			
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'DRY'	'DRY'	'DRY'
'DRY'	'WET'	'DRY'	'DRY'
'DRY'	'WET'	'DRY'	'DRY'
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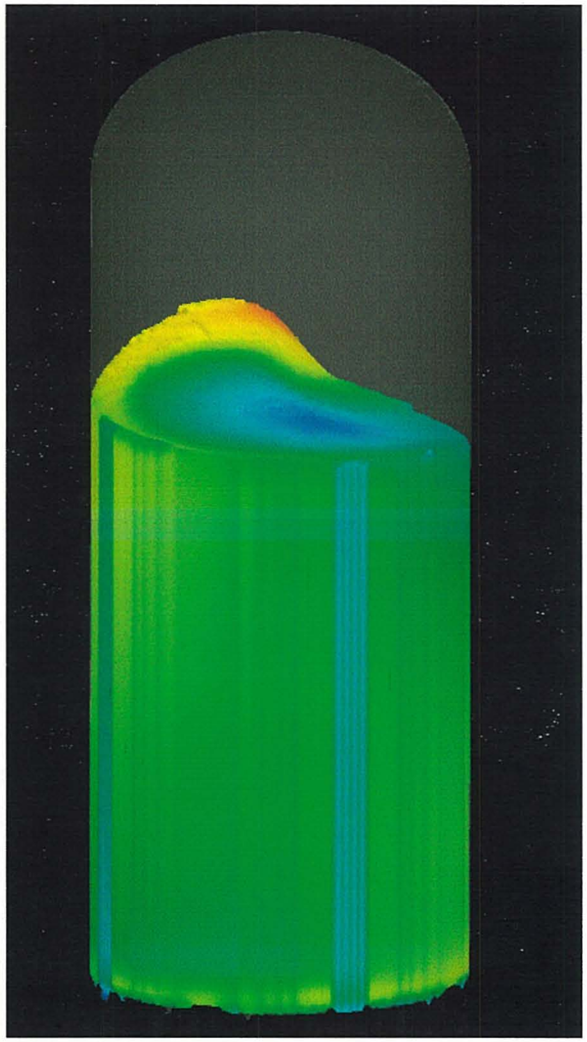


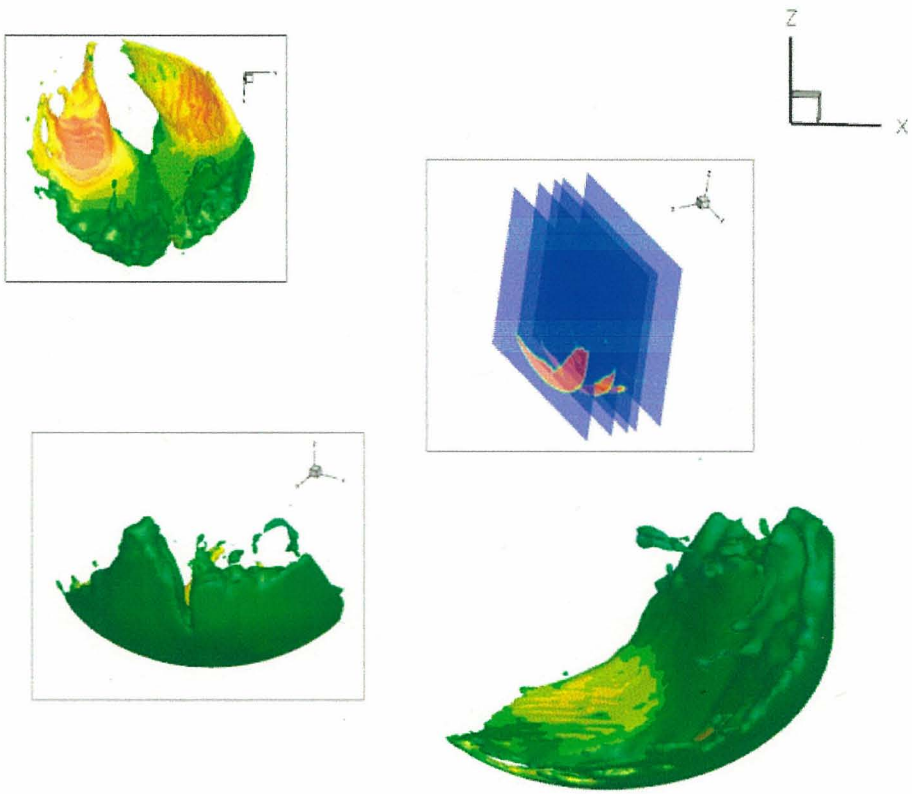
- CFD fluid slosh simulation is carried out for the duration of the coast period using trajectory 6DOF data
- Rotation and slosh events are identified and mapped from fine CFD volume mesh to coarse thermal surface mesh
- Shown here is an example of a slosh wave in a LH2 tank during a coast period.

'WET'	'WET'	'WET'	'WET'
'WET'	'WET'	'WET'	'WET'
'WET'	'WET'	'WET'	'WET'
'WET'	'WET'	'WET'	'WET'
'WET'	'WET'	'WET'	'WET'
'WET'	'WET'	'WET'	'WET'
'WET'	'WET'	'WET'	'WET'

0.991	0.992	0.992	0.991
0.991	0.992	0.992	0.991
0.991	0.992	0.992	0.991
0.991	0.992	0.992	0.991
0.9915	0.992	0.992	0.9905
0.992	0.992	0.99125	0.99075
0.995167	0.995333	0.995333	0.994833

Droplet Modeling

CFD Droplet Tracking



- Receives a 3D VOF matrix from Flow3D as a simulation result
- MATLAB subroutine parses the matrix. Uses an advancing front methodology to capture each droplet and their volumes and surface areas
- Can be used as an input source for a slosh model

Droplet Modeling

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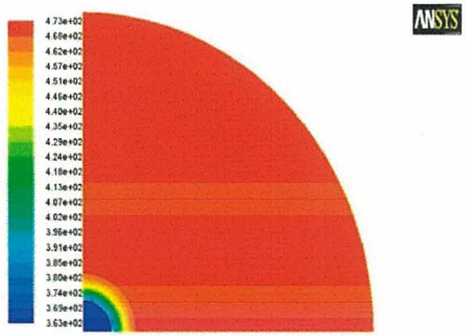
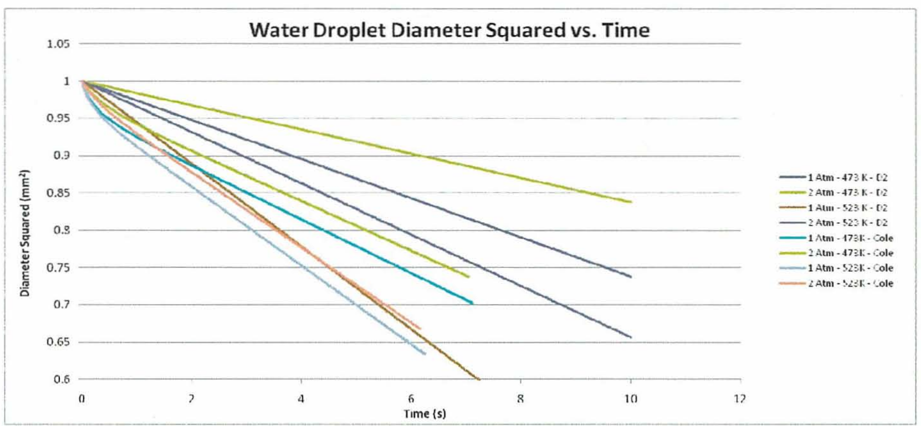
Droplet Evaporation

$$\frac{d\tau}{ds} = \frac{\chi}{\xi^2}(\mu - \Omega)$$

$$\chi = \frac{ln(\theta)}{Le_F} \qquad \mu = \frac{1-\tau}{e^{\chi} - 1}$$

$$\theta = \frac{1 - Y_{F\infty}}{1 - Y_{Fs}} \qquad \frac{d\xi^2}{ds} = -\lambda\chi$$

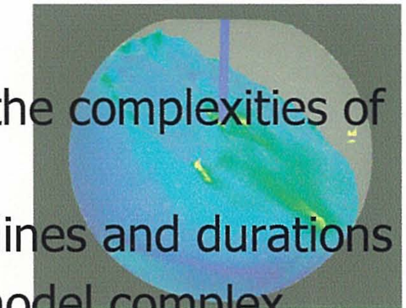




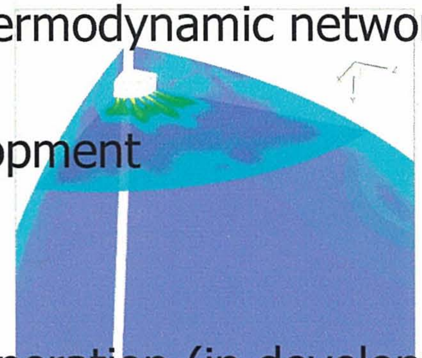
- Characterization of cryogenic droplet evaporation behavior
- Result is a set of analytical equations to solve the amount of liquid evaporated during a slosh event for one droplet
- Can be applied to multiple droplets.
- Still needs to be verified experimentally, if possible.

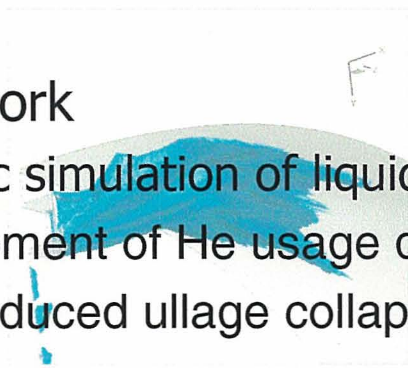
Conclusions

- Fully integrated models for generation of high fidelity predictions for propellant thermodynamic states and characterization have been developed



  - Models account for a variety of influences and reactions to the complexities of mission requirements in space environments
  - Models can be tailored to specific vehicles and mission timelines and durations
  - FLUINT pipe flow network simulation successfully used to model complex cryogenic thermodynamic behavior
  - Capability to include slosh baffle and propellant conditioning effects
  - Methodologies developed to map CFD predictions to thermodynamic networks within the models
  - Option to include ullage and liquid droplet/vapor development





- Future Work
  - Dynamic simulation of liquid extraction during engine operation (in development)
  - Development of He usage due to dome wetting
  - Slosh induced ullage collapse modeling